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Latest results on single electroweak boson production from the CMS experiment

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The production of W and Z bosons is one of the most prominent examples of hard scattering processes at hadron colliders. The measurements of the corresponding inclusive and differential cross sections provide important tests of perturbative quantum chromodynamics and parton distribution functions. Moreover, these processes constitute the main source of background for the searches for dark matter or other exotic final states, making the precise knowledge of W and Z boson kinematic spectra a fundamental tool to search for new physics. This paper reports a summary of the latest measurements of single electroweak boson production carried out by the CMS experiment at the CERN Large Hadron Collider. They are based on data collected at a centre-of-mass energy of 8 or 13 TeV. The measurements are performed exploiting the decay of W and Z bosons into electrons or muons, which provide a clean experimental final state with a low level of background. Results are corrected to the stable-particle level through unfolding techniques and compared with theoretical predictions obtained using several generators, allowing to validate different models for the parton shower and hard scattering processes. The main features of the selected analyses are illustrated and their role in the consolidation and development of our current knowledge of the electroweak sector is highlighted. Finally, the prospects for new measurements using the full dataset collected by CMS at 13 TeV by the end of 2018 are briefly discussed as well.

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1. Introduction

The Standard Model (SM) of particle physics describes matter in terms of fundamental particles and their interactions mediated by vector bosons. The W and Z bosons were discovered at CERN in 1983 [1, 2], yet they are still on the front line of the LHC physics programme. In particular, the mass of the Z boson is currently known with high precision, making this particle a precious standard candle for the calibration of the energy scale of electrons and muons. The production of W and Z bosons is one of the most prominent examples of hard scattering processes at hadron colliders. The corresponding inclusive and differential cross sections are predicted with next-to-leading order (NLO) or higher accuracy in perturbative quantum chromodynamics (QCD). The precision of the theoretical predictions is limited by the uncertainty in the parton distribution functions (PDF), missing higher order corrections and electroweak (EWK) radiative corrections. Therefore, these measurements provide stringent tests of perturbative QCD calculation and PDF.

The CMS experiment [3] at the CERN LHC has hitherto performed many cross section measurements for weak bosons produced in association with jets or heavy flavour quarks at different centre-of-mass energies. The measurements are generally in good agreement with the predictions over several orders of magnitude. This achievement was possible thanks to the extraordinary performance of the LHC machine: the unprecedented instantaneous luminosity reached by LHC has provided experimental physicists with large datasets, allowing for detailed studies of both well-known and rare EWK processes with cross sections as low as few fb.

This paper focuses on the production of singly produced W and Z bosons. At LHC, these processes are a constant presence in analyses targeting the search for dark matter or other exotic final states, which are characterized by large values of missing energy in the transverse plane (E_T^{miss}) due to the production of particles that do not interact with the detectors. The signal is generally expected as a broad excess of events in the E_T^{miss} distribution with respect to the irreducible SM backgrounds dominated by $Z/W{+}jets$ events, where E_T^{miss} originates from neutrinos in W and Z decays. Therefore, the precise experimental knowledge of kinematic spectra for SM processes, supported by robust theoretical calculations, is fundamental for any search for new physics. Moreover, the production of Z and W bosons plays a key role in other SM measurements as well. For example, the knowledge of their p_T distribution at very low p_T represents one of the leading source of uncertainty on the measurement of the W boson mass [4]. The precise measurement of this SM parameter (at the level of 10 MeV) would supply an extraordinary handle to test the internal consistency of the SM and, ironically, it could potentially provide a better hint to probe the possible existence of new physics than the direct searches themselves.

2. Common theoretical and experimental details

This paper describes the measurements of inclusive or differential cross sections for the production of W and Z bosons. The analyses are performed on data collected during the LHC Run I at a centre-of-mass energy of 8 TeV or on the datasets collected at 13 TeV during Run II up to 2016. Differential cross sections are measured as a function of many kinematic variables, such as the boson's p_T, the pseudorapidity (η) of the charged leptons in the decay or other suitable variables. They are usually normalized to the total cross section to take advantage of the partial cancellation

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of some experimental and theoretical uncertainties: for example, the largest experimental uncertainty on the absolute cross section comes from the knowledge of the integrated luminosity (about 3%) and it does not affect the ratio of cross sections.

Results are compared with predictions from several Monte Carlo (MC) generators, which differ in their approach to model the parton shower and/or the hard scattering. In the case of differential measurements, there is often no specific generator that can describe data in all the studied kinematic range. Assessing which generator provides the better description of data (and in which kinematic region) is a precious source of information for the theoretical community, because it can suggest the need for either additional higher orders in the calculations or a better accuracy in the modeling of the underlying processes.

From the experimental point of view, W and Z bosons provide a clean signature with a low level of background due to the production of isolated leptons with high p_T. The backgrounds consist of all SM processes generating electrons or muons in the final state such as top quark, diboson and τ lepton production. An additional source of background arises from QCD multi-jet production, where the leptons originate from the misidentification of jets or decays in flight of heavy flavour quarks. Backgrounds in the Z channel are almost negligible, while the W channel suffers from significant QCD contamination. The QCD background is estimated in a data-driven way using control regions, as simulations do not accurately describe the underlying processes, while other backgrounds are estimated directly from MC.

The measurements are performed in fiducial regions defined by the p_T and η thresholds for the lepton(s). The p_T thresholds are dictated by the trigger, so to comply with the limitation in the CMS readout bandwidth and storage space. They are typically about 20 (25) GeV for muons (electrons), lower for muons due to the higher purity of the selected sample. The η range is defined by the acceptance of the tracker, which covers the region with $|\eta| < 2.5$. Muons are selected up to $|\eta| = 2.4$ to ensure higher efficiency, while electrons can be selected up to 2.5 because the identification is complemented by the electromagnetic calorimeter.

The background-subtracted distributions are corrected to the stable-particle level with an unfolding technique. This procedure aims at removing from the measured distributions the effects of detector resolution, which induces a migration of events between neighbouring bins. The unfolding allows for direct comparison of data with theoretical predictions and analogue results from other experiments, without the need to pass generated events through a simulation of the CMS detector.

3. Measurement of W and Z boson $d\sigma/dp_T$ and Z boson $d^2\sigma/d\phi^* d|y|$ at 8 TeV

The p_T distribution of W and Z bosons can be computed with fixed-order perturbative QCD calculations for $p_T \gtrsim m_{Z/W}$. The fixed-order prediction diverges for $p_T \ll m_{Z/W}$ due to the appearance of large logarithmic terms induced by soft gluon radiation and other non-perturbative effects [5], for which resummation techniques are required. Therefore, measurements at $p_T \lesssim 10$ GeV are extremely precious. CMS has measured the W and Z boson p_T spectra and their ratio using data collected at 8 TeV during a special low-luminosity run corresponding to an integrated luminosity of 18.4 pb^{-1} [6]. The low number of simultaneous proton-proton collisions (pileup) results in less background and improved resolution. The production of W bosons is studied in both electron and muon decay modes, while the production of Z bosons is studied using only the

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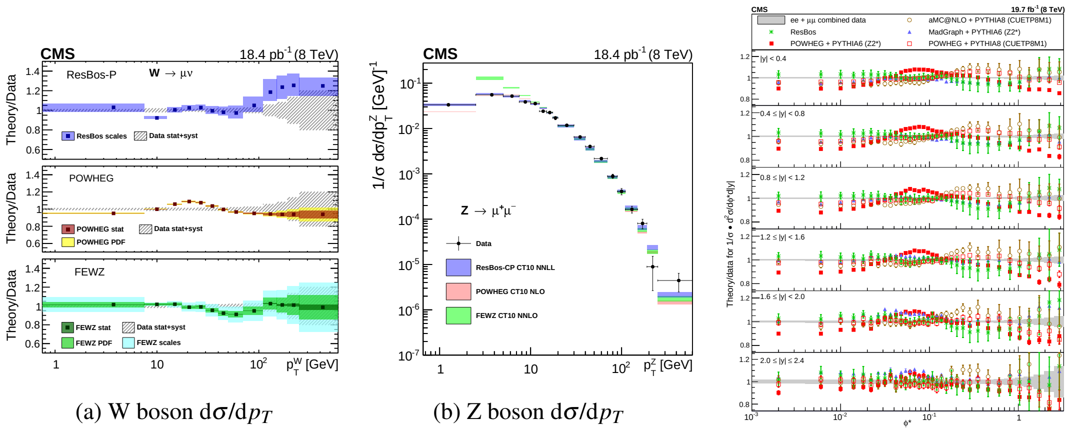
dimuon decay channel. The Z boson signal is extracted by counting events with a pair of oppositely charged muons passing some predefined identification criteria and with a reconstructed invariant mass satisfying $60 < m_{\mu\mu} < 120\,\mathrm{GeV}$. In the W channel, the signal is obtained from a fit to the E_T^{miss} distribution in each p_T bin. The QCD component in the fit is estimated using a dedicated QCD-enriched control region defined by inverting the lepton identification and isolation criteria. Figures 1a and 1b show the ratio of predicted and observed normalized differential cross section $\mathrm{d}\sigma/\mathrm{d}p_T$ for the W boson, and the normalized p_T distribution for the Z boson, respectively. Data are compared with ResBos-P, POWHEG and FEWZ generators. FEWZ implements fixed-order calculations without resummation and shows a divergent behaviour at low p_T. The experimental uncertainty on the Z boson p_T is dominated by the uncertainties in the magnitude of the p_T of the final state leptons. However, thanks to the excellent spatial resolution of the CMS tracker, the angles subtended by the leptons can be measured with much higher precision. This feature was exploited by CMS to measure the double differential cross section of Z bosons as a function on the boson rapidity (y) and the ϕ^* variable using $19.7\,\mathrm{fb}^{-1}$. The ϕ^* variable is correlated with p_T by the approximate relation $\phi^* \approx p_T/m_{\ell\ell}$, but depends only on angular variables and allows to investigate the low-p_T region with higher resolution. Figure 1c shows the comparisons with a variety of theoretical predictions for the normalized cross section $\mathrm{d}^2\sigma/\mathrm{d}\phi^*\mathrm{d}|y|$. Better models of the hard-scattering process, such as the one provided by MADGRAPH + PYTHIA 6, lead to an improved agreement with the data. At the same time, the comparison with POWHEG interfaced with two different versions of PYTHIA demonstrates the importance of the underlying event model and hadronization tune to yield the most accurate description of data.



(a) W boson $\mathrm{d}\sigma/\mathrm{d}p_T$ (b) Z boson $\mathrm{d}\sigma/\mathrm{d}p_T$ (c) normalized $\mathrm{d}^2\sigma/\mathrm{d}\phi^*\mathrm{d}|y|$

Figure 1: Left: ratio of predicted over measured W boson normalized $\mathrm{d}\sigma/\mathrm{d}p_T$ for different generators. Middle: measured Z boson normalized $\mathrm{d}\sigma/\mathrm{d}p_T$, compared to predictions from three generators. Right: double differential Z boson cross section as a function of the boson rapidity y and the ϕ^* variable from the combination of the electron and muon channel. The observed distributions are compared with predictions obtained using different combinations of hard scattering and parton shower generators. Taken from [6, 7]

4. Measurements at 13 TeV

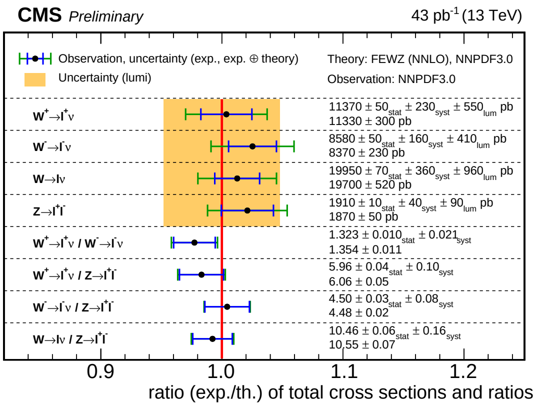
CMS has measured the inclusive W and Z production cross sections at 13 TeV using $43\,\mathrm{pb}^{-1}$

of data [8]. Despite the small dataset used for this analysis, the relatively large cross section allows to perform a lot of interesting measurements with very high precision. The analysis techniques are the same as those described in section 3. The measured cross sections for Z and W bosons and their ratio are shown in fig. 2a. The uncertainty is always limited by the systematic ones and the largest one comes from the integrated luminosity, which cancels out along with other theoretical uncertainties in the ratios. The ratio of the cross section in the muon and electron channels are also used to test the lepton flavour universality, showing good agreement with the SM. These results complement analogue measurements performed by CMS at 7 and 8 TeV and confirm the predicted increase of the cross sections with centre-of-mass energy.

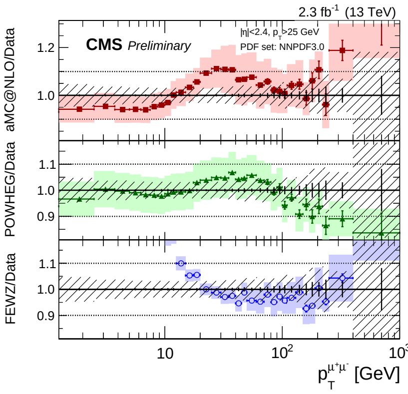
The measurement of the Z boson inclusive cross section in the muon decay channel has been repeated using the full 2015 dataset at 13 TeV (2.3 fb^{-1}) and extended with the measurement of the differential cross section as a function of several kinematic variables, such as Z boson p_T and y, ϕ^* and the p_T of the muon with the highest energy [9]. The inclusive measurement is in good agreement with theoretical predictions computed at NNLO QCD + NLO EWK. However, no generator is able to provide an accurate description of the measured differential cross sections in all the phase space of the analysis. For example, as reported in fig. 2b, the prediction from FEWZ diverges at low p_T, but successfully describes data at intermediate and high p_T, while POWHEG shows the opposite behaviour.

The production of lepton pairs in the Drell–Yan process represents the main source of background for searches for new resonances decaying into lepton pairs, whose expected signal is a narrow peak in the exponentially decreasing dilepton invariant mass spectrum. CMS has measured the differential Drell–Yan cross section in the muon channel using a dataset of 2.8 fb^{-1} collected in 2015 [10]. The measurement is currently limited by the statistical uncertainty for masses above $\approx$ 500 GeV, followed by the systematic uncertainty on the resolution on the muon p_T and on the background estimate. The much larger dataset collected by CMS since 2015 (more than 100 fb^{-1} are expected by the end of 2018) will help reduce the statistical uncertainty and extend the mass range beyond the current limit of 2 TeV. However, the measurement in the muon channel is expected to be limited by the muon p_T resolution, which gets worse at high p_T. The addition of the electron channel will complement and actually improve this measurement, since the precision on the measurement of the electron energy is driven by the energy resolution of the electromagnetic calorimeter, which improves at higher energy.

The measurements presented so far in this paper concern known processes of the SM and have been carried out on a relatively small dataset. However, the much larger amount of data recorded by CMS also opens the possibility to observe and study in detail some rare processes predicted by the SM. For example, CMS has presented the observation of the Z boson rare decay to a ψ meson and two oppositely charged same-flavour leptons (electrons or muons), where ψ represents the sum of J/ψ and ψ(2S)$\to J/\psi X$ [11]. The analysis is based on 35.9 fb^{-1} collected in 2016. The signal is observed with a significance larger than 5 standard deviations and, removing the contributions from decays of ψ(2S) into J/ψ, is interpreted as being entirely from $Z \to J/\psi\ell^+\ell^-$ ($\ell = \mu, e$). The Feynman diagram for the scrutinized process in illustrated in fig. 3a. Events are selected requiring the presence of two pairs of same-flavour isolated leptons with opposite charge, whose associated tracks must originate from the same hard scattering vertex. Only the muon decay channel is considered for ψ mesons, since the available triggers for low-p_T electrons would not guarantee high enough efficiency and purity. Signal events are selected by imposing constraints on the invariant masses of the lepton pairs, consistently with the masses of the ψ meson and the Z boson resonance. The signal yield is obtained from an unbinned extended maximum-likelihood fit of the distribution in the two invariant mass variables $m_{\mu^+\mu^-}$ and $m_{\mu^+\mu^-\ell^+\ell^-}$ for J/ψ and Z respectively. The projections in each variable for the muon sample are shown in figs. 3b, 3c respectively, along with the components resulting from the fit. In order to remove some systematic uncertainties, the result is presented in terms of fiducial branching fraction $\mathfrak{B}$ relative to that of the Z boson decaying into four muons: $\mathfrak{B}(Z \to J/\psi\ell^+\ell^-)\,/\,\mathfrak{B}(Z \to 4\mu) = 0.70 \pm 0.18(stat) \pm 0.05(syst)$. The measurement is still limited by the size of the analyzed sample. In addition, this result is obtained with the assumption of no J/ψ polarization: extreme polarization scenarios imply a variation as large as 20% and their investigation requires more data. Therefore, several improvements are expected to come from the analysis of the full dataset collected by CMS by 2018.

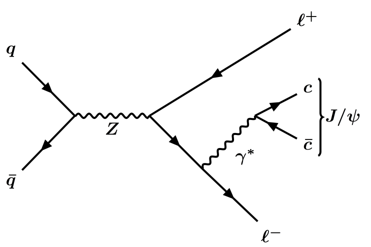


(a) W and Z boson inclusive cross sections and ratios

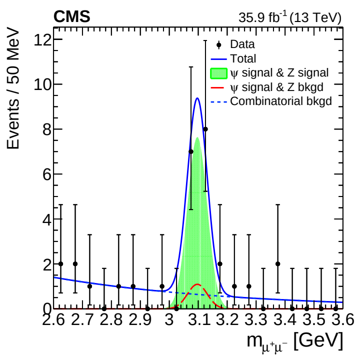


(b) Differential Z boson $d\sigma/dp_T$ ratios

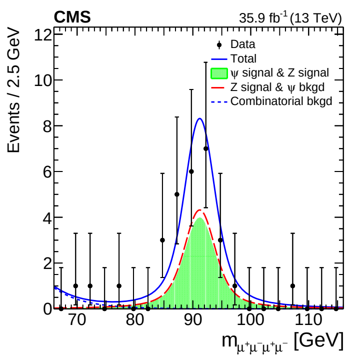
Figure 2: Left: summary of inclusive cross sections for Z and W bosons and their ratio. Right: ratio of predicted and measured differential cross sections as a function of Z boson p_T, using three different generators. Taken from [8, 9]



(a) Feynman diagram: $Z \to J/\psi\ell^+\ell^-$



(b) $J/\psi \to \mu^+\mu^-$



(c) $Z \to \mu^+\mu^-\mu^+\mu^-$

Figure 3: Left: leading-order diagram for the $Z \to J/\psi\ell^+\ell^-$ process. Middle and right: J/ψ and Z mass distributions in the four muon final state, along with the components resulting from the fit. Taken from [11]

5. Conclusions

Several measurements targeting the production of Z and W bosons have been carried out by CMS and are reported in this paper. Most of the latest results are based on data collected at 8 TeV or on a limited dataset at 13 TeV. These measurements are of paramount importance for searches for new physics because they help consolidate our current knowledge of the electroweak sector, leading to more accurate background predictions. Results are compared with predictions from many generators, allowing to test the validity domain of different models for parton shower and/or hard scattering. Most analyses are limited by systematic uncertainties, dominated by the one on the integrated luminosity. However, several improvements are expected with the inclusion of the full dataset at 13 TeV collected by CMS. Indeed, the larger dataset will allow to extend the kinematic range of differential cross section measurements to higher values of p_T and mass, as well as open the possibility to investigate rare processes not yet observed.

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